The influence of LER and LWR on angular resolved EUV scatterometry

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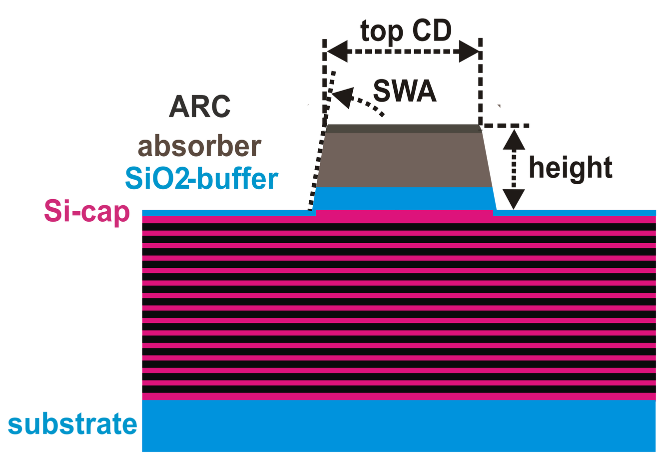
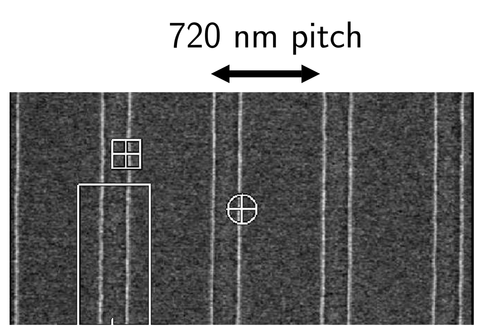
Motivation

Scatterometry, the analysis of light diffracted from a periodic structure, is a versatile metrology for characterizing periodic structures regarding critical dimension and other profile properties. It is currently one of the most commonly used techniques in quantitative wafer metrology. As the structures become smaller and smaller, fewer and fewer propagating diffraction orders exist which do not carry enough information about the structure any more. Shorter wavelengths are therefore desirable. The Physikalisch-Technische Bundesanstalt (PTB) operates an EUV reflectometry facility at the electron storage ring BESSY II, particularly to support the development of Extreme Ultraviolet Lithography. The short wavelength of EUV is advantageous, since it provides more propagating diffraction orders as compared to the longer wavelength UV and VIS radiation. The short wavelength also increases the sensitivity to small structural features, particularly roughness. We present a method to numerically estimate changes in measured diffraction intensities in angular resolved scatterometry induced by both line edge roughness (LER) and line width roughness (LWR). The model can be used to include the estimation of the roughness directly into the structure reconstruction algorithm. We discuss the consequences for profile reconstruction for the example of absorber lines with trapezoidal cross section.

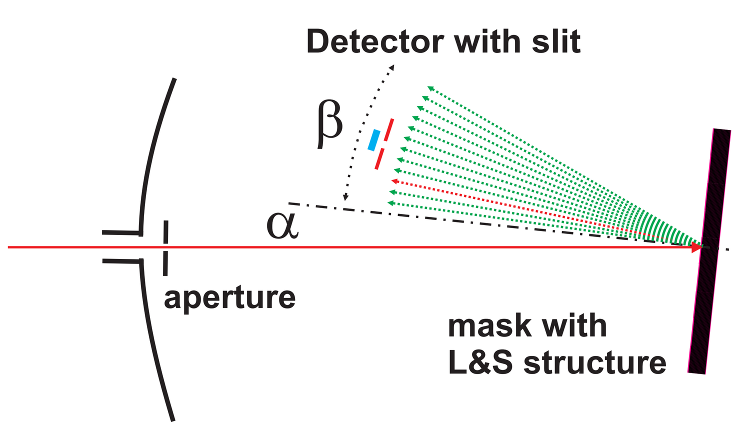
Scatterometry

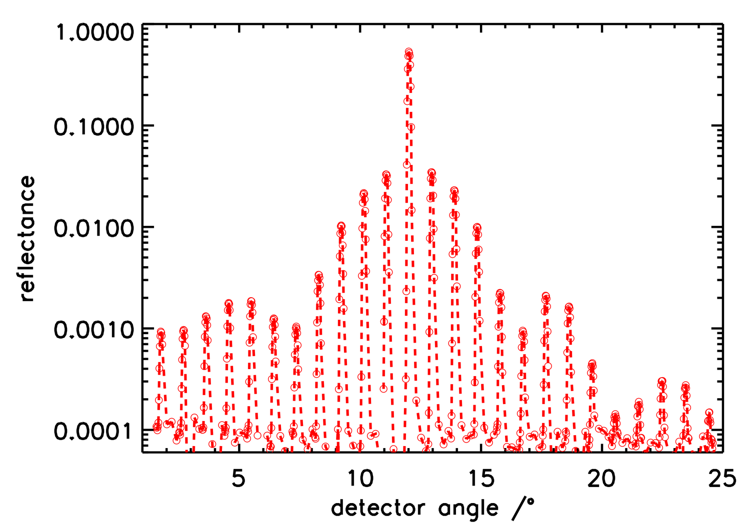
Experimental set-up





SEM image of an EUV photomask and its profile scheme including the geometrical parameters of the absorber line. The absorber lines are placed periodically on top of a reflective Mo/Si multilayer.

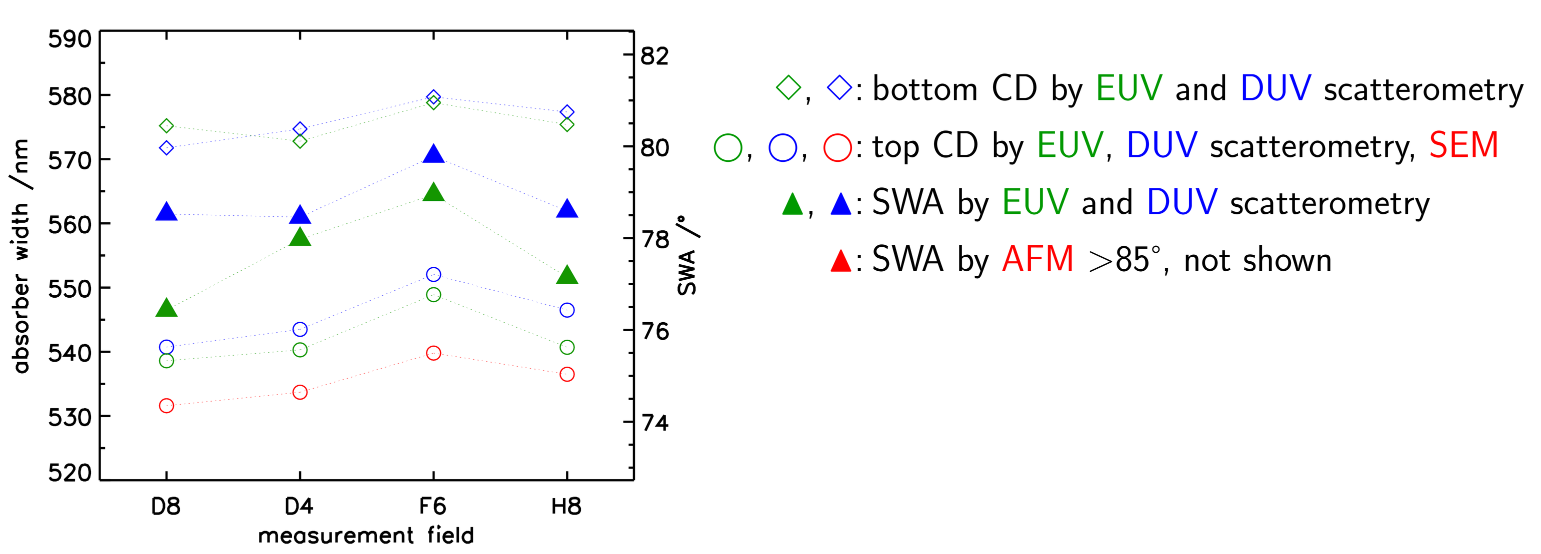




Scatterometry measurement. The detector angle is scanned in the plane of incidence perpendicular to the lines, at a fixed incidence angle of α=6° to measure discrete diffraction orders using monochromatized radiation. Right: measured diffraction pattern of 140 nm wide absorber lines at 840 nm pitch, λ=13.654 nm

Inverse scatterometric problem

The electric field of light diffracted at periodic boundary conditions can be determined numerically by solving Maxwell's equations. An optimization algorithm including this forward simulation can solve the non-linear least squares problem for the measured and calculated efficiencies to fit the geometrical parameters of the absorber line [1],[2].



The photomask has been measured by different methods such as SEM, AFM, DUV scatterometry at 193 nm, and EUV scatterometry around 13.5 nm. While the values for the line width (CD) agree acceptably well, a discrepancy is observed for the sidewall angle (SWA) between the DUV/EUV scatterometry (SWA<80°) and the AFM measurements (SWA>85°). We investigate the impact of line roughness which disturbs the structure periodicity which is, in turn, a premise for the scatterometry data evaluation.

Modeling of line roughness

Fraunhofer Diffraction

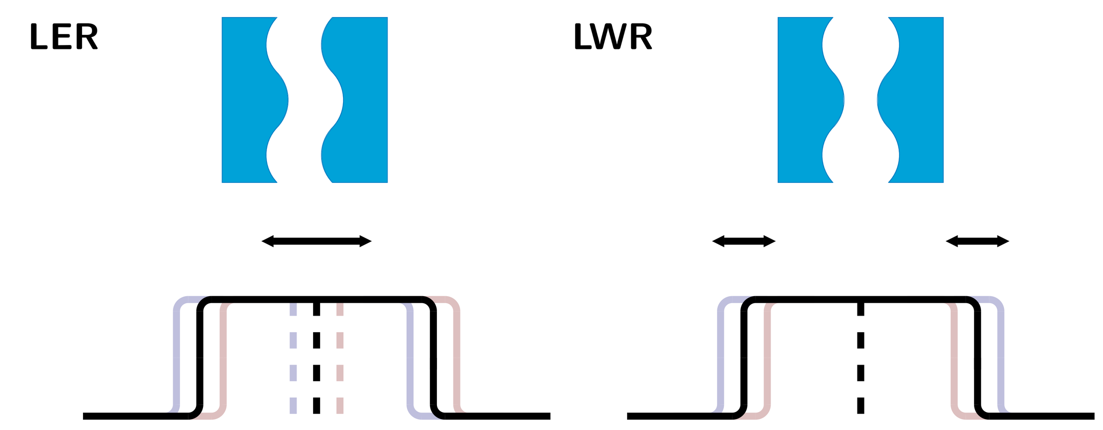
The forward simulation of the diffraction as described above is not suited to investigate the effect of line roughness, since the periodicity of the boundary conditions is not given. Therefore, we choose a simple analytic model and consider the Fraunhofer diffraction of a binary grating in 1D.

$$E(k) \sim \mathcal{F}\{r\}(k)$$

The electric field as a function of the wavenumber $k = k_{\text{scattered}} - k_{\text{incident}}$ in the far field approximation is given by the Fourier transform of the reflectivity function r that has in this case the codomain $\{0, 1\}$.

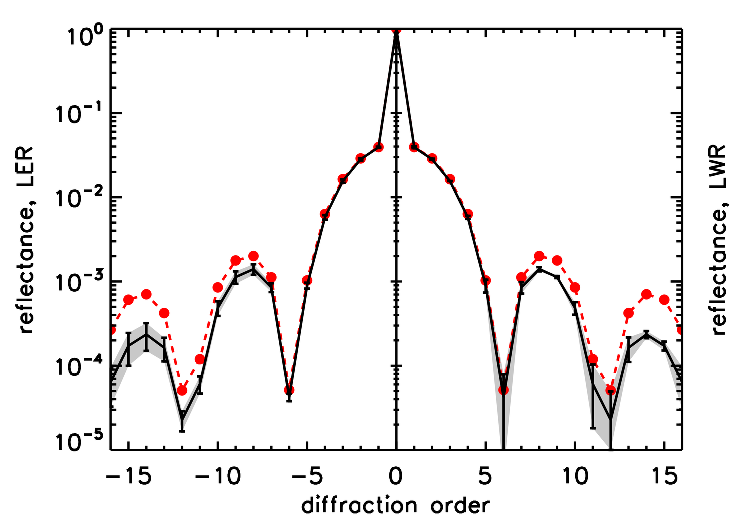
Line Edge & Line Width Roughness

Next, we include the concept of line roughness into the model. In order to model the LER, the pitch and CD are kept constant, while the line center positions are assumed to be randomly distributed around their periodic reference positions. In the case of LWR, the pitch and the periodic line center positions are fixed. The line widths are randomly distributed around the nominal CD.



In both cases, we assume uncorrelated Gaussian distributions for each line. Then, it is possible to derive the expectation values for $E(k)$ and the diffracted intensity $I(k) \sim |E(k)|^2$, and to determine the standard deviation $\sigma_I(k)$.

Effect of line roughness



- undisturbed diffraction intensity $I_0(k)$
- disturbed diffraction pattern: expectation value $I(k)$ & standard deviation $\sigma_I(k)$
- range of $I(k) \pm \sigma_I(k)$
- 145 nm dark lines at 840 nm pitch
- LER: line center positions with mean: nominal, σ=10 nm
- LWR: line width deviations with mean: zero, σ=20 nm
- number of lines N=100

LER

$$I(k) = I_0(k) \exp\left(-\sigma^2 k^2\right) \qquad (1)$$

$$\sigma_I(k) = \frac{4\sigma}{w\sqrt{N}} \left|\sin\frac{kw}{2}\right| \sqrt{I(k)}$$

LWR

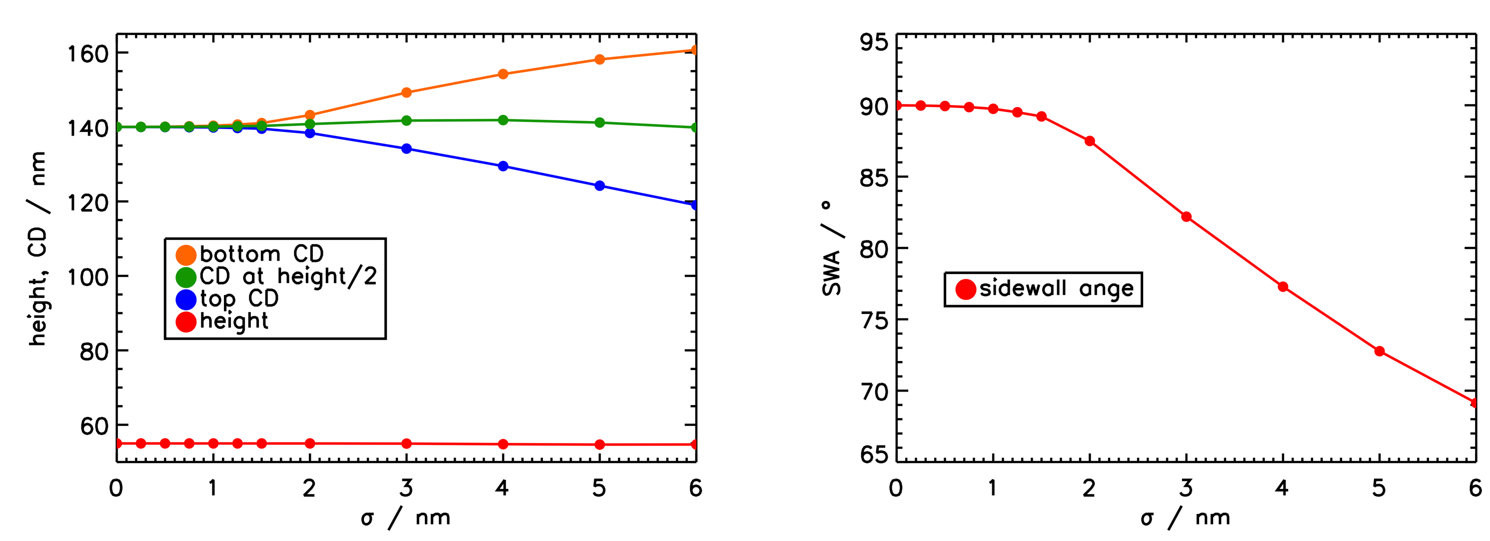
$$I(k) = I_0(k) \exp\left(-\frac{\sigma^2}{4} k^2\right)$$

$$\sigma_I(k) = \frac{2\sigma}{w\sqrt{N}} \left|\cos\frac{kw}{2}\right| \sqrt{I(k)}$$

The calculations yield an attenuation factor of Debye-Waller type for the intensity in both cases, and phase-shifted distributions σ_I of the diffraction pattern for LER and LWR. w stands for the nominal width, N for the total number of the lines.

Impact on structure reconstruction

To investigate the effect of roughness on the structure reconstruction algorithm, we generate artificially disturbed input data sets. To this end, the diffraction efficiencies obtained by a forward simulation using an FEM Maxwell solver are multiplied by the Debye-Waller factor (1). The three parameters height, top CD and bottom CD of the absorber line are optimized, while all material properties and the geometry of the multilayer are fixed. It is assumed that the lines have a trapezoidal and symmetric cross section.



The values at σ=0 correspond to the parameters of the initial forward simulation. The reconstructed values for the line's height and the CD at 50% height remain stable in the considered range of roughness. In contrast, we observe an increasing discrepancy between the top CD and the bottom CD which results in rapidly decreasing sidewall angles at increasing roughness values [3].

Conclusion

The influence of line roughness on the diffraction intensities can be described analytically by an exponential damping factor of Debye-Waller type in the Fourier optic approximation. Roughness also inherently adds significant statistical variations for measurement fields of finite size. The consequences for profile reconstruction are presented for trapezoidal absorber lines of an EUV photomask, where structure roughness reduces the reconstructed sidewall angle in angular resolved scatterometry, whereas other parameters like line width and height are less affected. These effects have to be taken into account when scatterometry data are evaluated.

References

[1] F. Scholze and C. Laubis, in *EMLC 2008*, U. Behringer, ed. (VDE VERLAG, 2008), pp. 374–382.

[2] J. Pomplun et al., Proc. SPIE **7028**, 70280P (2008).

[3] A. Kato and F. Scholze, Appl. Optics **49**, in press (11/1/2010)

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